The Meteorological Magazine

May 1992

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Forecasting seasonal long rains in Kenya
The spring of 1991

Met.O.1004 Vol. 121 No. 1438

The
Meteorological
Magazine

May 1992
Vol. 121 No. 1438

551.509.313:551.465

The role of ocean models in FOAM

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Summary

FOAM (the Forecasting Ocean Atmosphere Model) is planned to form the basis of an ocean forecast system for the Atlantic and Arctic Oceans. Synoptic features in the ocean have smaller space scales than in the atmosphere, and so require more observations to define them and greater computer power to simulate them. Satellites, such as ERS-1, will supplement the in situ *data during the 1990s, and the power of supercomputers continues to increase. It is now possible to develop model-based systems for forecasting the ocean. FOAM will mimic the numerical weather prediction system at the Meteorological Office. An essential component of FOAM will be the use of manual input to the model to enhance the quality control of observations and to make use of data which cannot be used directly by the computer system.*

1. Introduction

Computers have been used to forecast the weather for many years with increasing accuracy (Meteorological Office 1988). Numerical models, based on the 'laws' of physics, form the basis of the Numerical Weather Prediction (NWP) systems. The ocean obeys the same laws as the atmosphere, and there is no theoretical reason why ocean forecasts should not be produced in the same way.

FOAM, the Forecasting Ocean Atmosphere Model, sets out to provide a physically based system for forecasting the temperature, salinity, and current structure of the Atlantic and Arctic Oceans.

This paper aims to explain why it has not been practical to produce ocean forecast models until the 1990s, and then describes the essential components of a computerized forecasting system. This involves a discussion of the models themselves and of the methods for inserting observations into the models. This is followed by a description of how the quality of forecasts can be improved by involving humans in the forecast cycle. Finally the reasons for using models in the FOAM system are summarized.

2. Evolution of the ocean circulation

Just as the atmospheric circulation is driven by the sun's energy, that of the ocean is driven primarily by the fluxes of heat, fresh water, and momentum across the air–sea interface (Foreman 1990). In response to these, the physics governing ocean circulation produce the large-scale flow patterns, within which smaller features may develop, such as fronts and eddies.

Atmospheric disturbances (depressions and anti-cyclones) have a major and rapid impact on the upper ocean, determining changes in the depth and temperature of the mixed layer on time-scales of hours to days. The spatial scale of these features is of the order of thousands of kilometres and they have a typical lifetime of a week.

The ocean also generates its own fronts and eddies. Development of eddies in the ocean is slower than in the atmosphere (Gill (1982) p. 569). Typically, Gulf Stream rings grow on time-scales of a week and have lifetimes of a month. Space-scales of ocean eddies are much smaller than those of the atmosphere, typically 200 km (Fig. 1).

On a seasonal time-scale the atmospheric climate influences the large-scale circulation patterns of the ocean. As an example, Fig. 2 shows the impact of

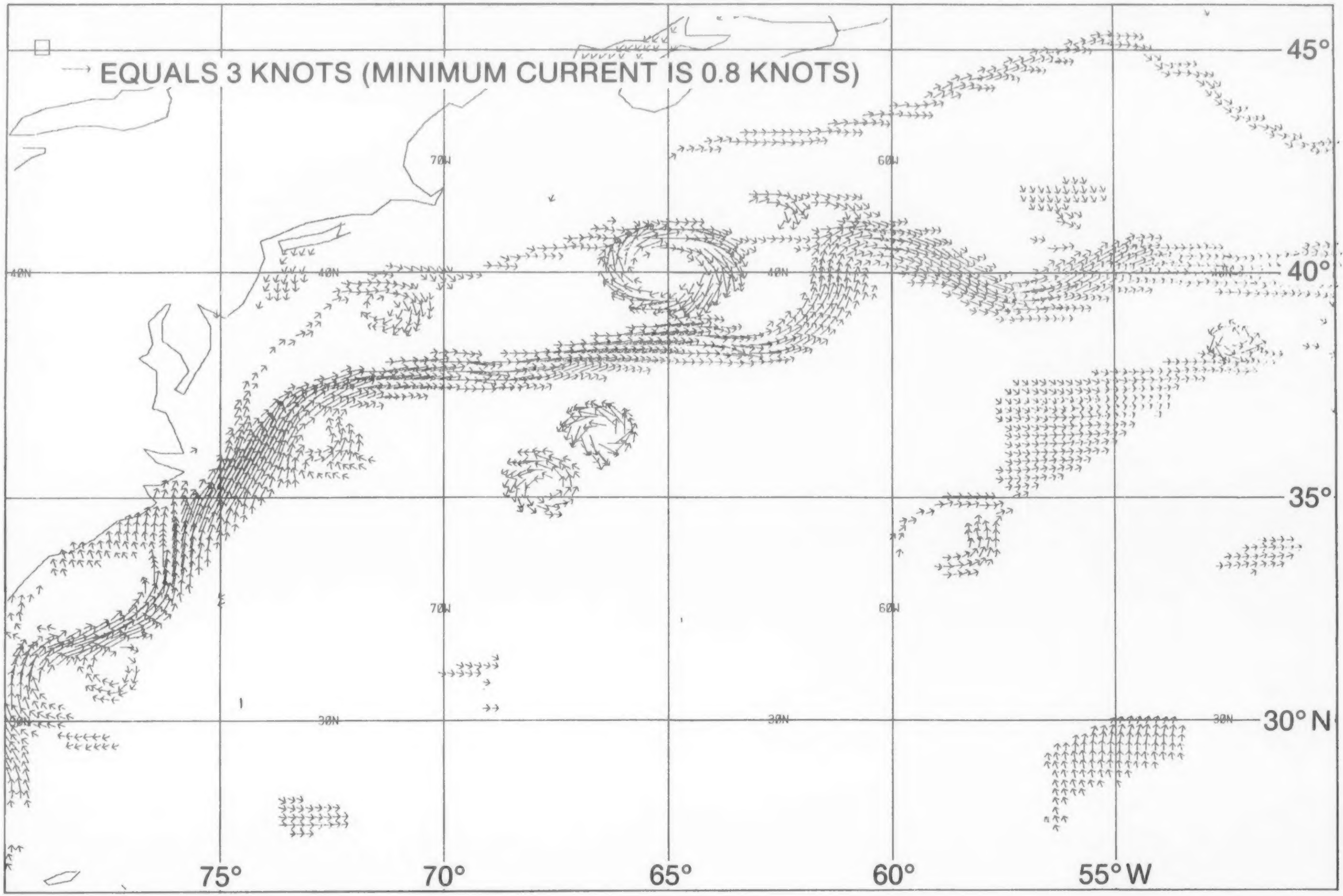

Figure 1. Ocean currents in the north-west Atlantic on 9 June 1991. Only currents greater than 0.8 kn are shown. (Reproduced with permission of M. Clancy, Fleet Numerical Oceanography Center.)

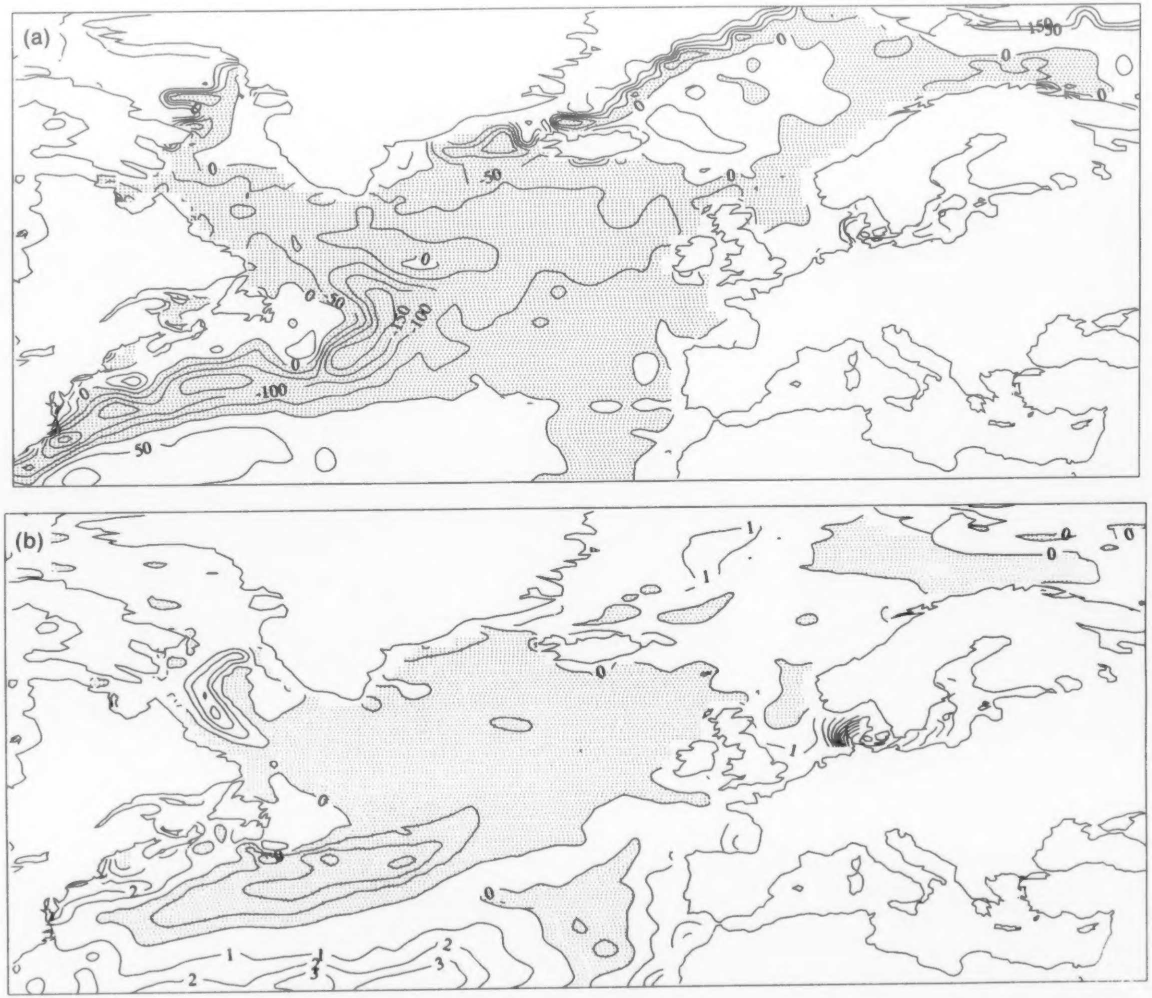

Figure 2. Impact of different surface flux estimates on an integration of a 1 degree resolution Atlantic model in the north-west Atlantic. Differences are for 6-month integrations for the winter of 1989/90 run using climatological fluxes minus a run with NWP derived fluxes. (a) Difference between six-month average of fluxes (50 W m^{-2} contour interval), and (b) difference between sea surface temperatures after 6 months of simulation (1 °C contour interval). Negative areas are stippled.

driving an ocean model with two different sets of surface fluxes. In the control, the fluxes used were derived from observed climatologies. The perturbation integration used surface fluxes from the Meteorological Office NWP suite. In both cases the fluxes were applied to an ocean model of the Atlantic for the 6 winter months. Fig. 2(a) shows the differences between the heat fluxes into the ocean averaged over the six months. Most of the structure in the Gulf Stream region is due to the greater horizontal resolution of the NWP data. There are large differences in other areas which are typical of inter-annual variability. Fig. 2(b) shows the difference in sea surface temperature (SST) between the two simulations at the end of the 6 months. Differences of one degree are common (and are typical of the observed interannual variability). The ocean therefore responds to the seasonal climate of the atmosphere. The space-scale of this response is large compared to that of the ocean eddies.

3. Observing the ocean

Different aspects of the ocean circulation have different time- and space-scales associated with them. Eddies in the ocean are typically an order of magnitude smaller than in the atmosphere, so that to obtain as accurate synoptic analyses as those from NWP correspondingly more observations would be needed.

Fig. 3 shows the locations of all observations of the ocean vertical structure for the Atlantic received in real time by the Meteorological Office during May 1991. Although there are regions (such as the eastern seaboard of the United States) where there is dense coverage of BATHY data (temperatures only), most of the ocean is unsampled. To resolve eddies would require observations about 25 km apart over the whole region in which eddies are expected (including the Iceland–Faeroes Gap). A full description of the ocean density requires salinity as well as temperature to be reported. The number of TESAC reports (which may contain both temperature

Figure 3. Distribution of BATHY and TESAC reports received at Bracknell in the Atlantic during May 1991. BATHY reports are indicated by circles, TESACs by crosses.

and salinity observations) during May 1991 can be seen to be small.

The horizontal distribution of BATHY and TESAC reports is inadequate for the task of determining the synoptic evolution of ocean eddies without further information. Considering the vertical distribution of reports is even less encouraging. Fig. 4 shows the depths to which observations extended in 1988. Although some of the more useful TESAC reports reached 2000 m, most of these were made by Ocean Weather Ship 'C', which no longer reports. Observations of the ocean below 600 m are rare.

Design of a system to analyse the ocean must also take into account the delays in receiving observations. As may be seen in Fig. 5, many BATHY and TESAC observations were still being received 3 days after the time for which they are valid.

By far the most plentiful observations of the ocean are of its surface temperature. There are two main sources of these data: ship reports and satellite measurements. Satellite infrared measurements have high spatial resolution, but cannot be made through cloud. Some satellites have used microwave sensors to measure sea surface temperature. Although observations may be made through cloud, they are of lower accuracy and resolution than those made using infrared instruments.

SEASAT in the 1970s, and GEOSAT during the 1980s, carried altimeters capable of measuring the height of the satellite above the ocean surface. Several successor satellites to these are planned for the 1990s, starting with ERS-1. After careful correction these observations may be used to derive information about the vertical mean circulation in the ocean. Data are derived along sub-satellite tracks, instead of the more familiar swathes of the sea-surface-temperature measurements. This means that deducing variations along the track is straightforward, but that variations perpendicular to the track can only be determined with the resolution of the spacing between tracks in both space and time. ERS-1 and other oceanographic missions carrying altimeters are designed to be flown in 'repeat orbits' in which the same point on the Earth is overflown on many orbits. A characteristic of the repeating orbits is that high spatial resolution is accompanied by low temporal resolution. The choice of orbit is thus a compromise between the needs of different users, and ERS-1 is expected change its orbit several times during its life.

It is only the introduction of satellites such as ERS-1 and development of new observation systems, such as the Natural Environment Research Council's 'AUTOSUB' project (Baker 1991) which will make it possible to observe the ocean in enough detail to make ocean forecasting a practical proposition.

4. Modelling the ocean

At its heart FOAM will contain numerical models of the atmosphere and ocean. That for the atmosphere will be the same as that used for NWP by the Meteorological Office (Wilson *et al.* 1990). This will communicate with a model of the ocean built using the same physical principles derived from Bryan and Cox (1972).

Underlying the ocean model are Newton's 'laws' of motion as they apply to a continuous fluid. Equations for conservation of heat, salt, momentum, and mass form the basis of the model. These are represented using a 'finite difference' approach, in which the ocean is divided into a large number of cuboids (in the early stages of FOAM these will have dimensions approximately 100 km (later 30 km) in the horizontal and 5 m in the vertical in the upper ocean). Numerical techniques based on finite difference approximations are used to approximate continuous equations governing ocean flow. These are solved using a computer for each model box and for each time-step. The forecast is thus built up of a sequence of 'mini forecasts' of a few minutes duration. The region expected to be covered by the model is shown in Fig. 6 and the physics represented within it in Fig. 7.

In the absence of observations (such as when producing a forecast) the ocean model responds only to its internal physics and to the fluxes of heat, fresh water, and momentum through the ocean surface, which are calculated by the NWP model. In many data-sparse areas forecasts would be the sole source of information about the ocean.

Techniques for modelling the ocean are similar to those used in numerical weather prediction. Computing demands of the ocean models are greater because of the smaller scales of ocean features. Weather forecast models use state-of-the-art supercomputers. It is only during the 1990s that supercomputers will become powerful enough to run ocean models for routine forecasts, and even then the models will continue to be limited by the computer power available.

5. Data assimilation

Data assimilation is the process of including ocean observations into the numerical model. This task is complicated by several factors, including: not enough observations to define the state of the ocean at any one time, observations have errors, observations may not be representative of the larger-scale ocean around them (e.g. through internal wave activity), the ocean model cannot resolve all scales of motion, and the physics included in the numerical model are not complete. Errors introduced by these factors grow during the forecast, and so frequent correction of the model is required to obtain realistic forecasts.

Ocean data could be used to analyse the state of the ocean without use of an ocean model. Fig. 3 demonstrates that analyses produced in this way would be lacking in detail.

Fig. 8 illustrates how observations are used in conjunction with a forecast model to produce estimates of the ocean state at a given time. Information available

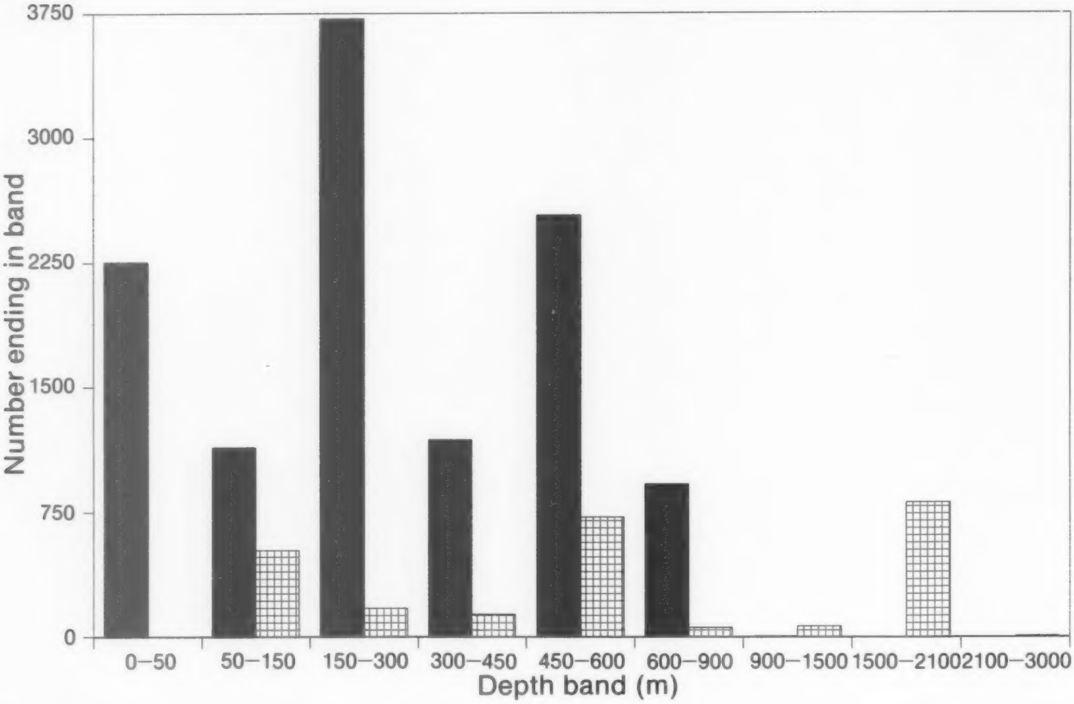

Figure 4. Distribution of maximum depths (in metres) reported in ocean observations for the Atlantic during 1988. BATHY reports indicated by the solid areas and TESAC reports by the shaded areas.

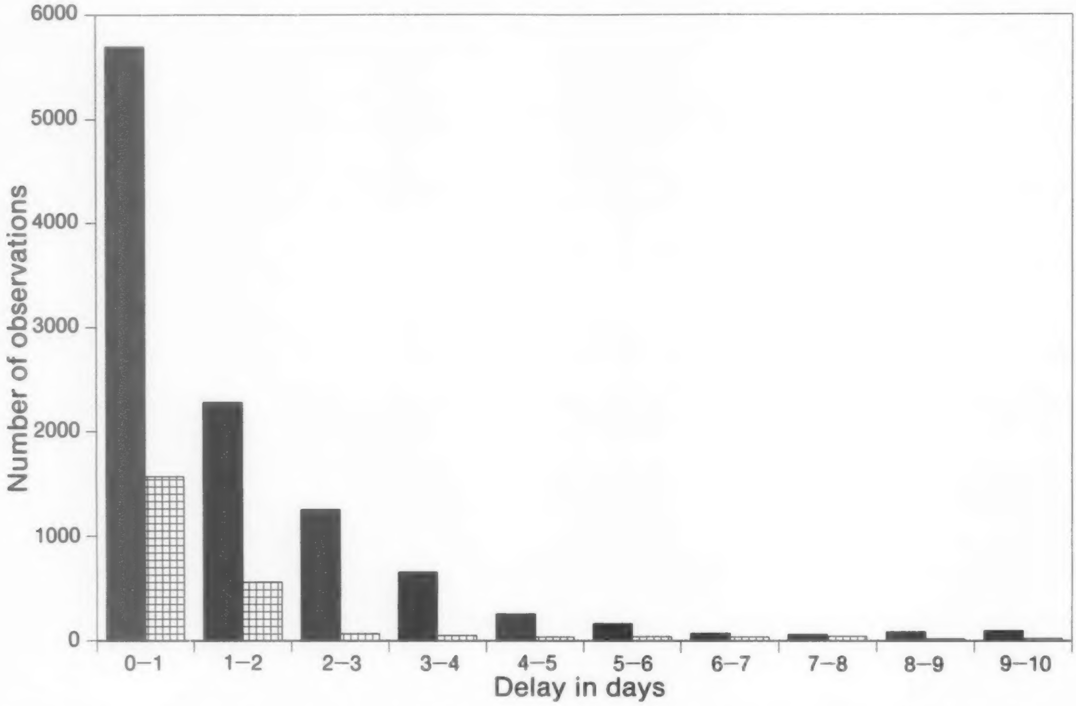

Figure 5. Distribution of the time delay between observations being made and receipt of the reports at Bracknell during 1988. BATHY reports indicated by the solid areas and TESAC reports by the shaded areas.

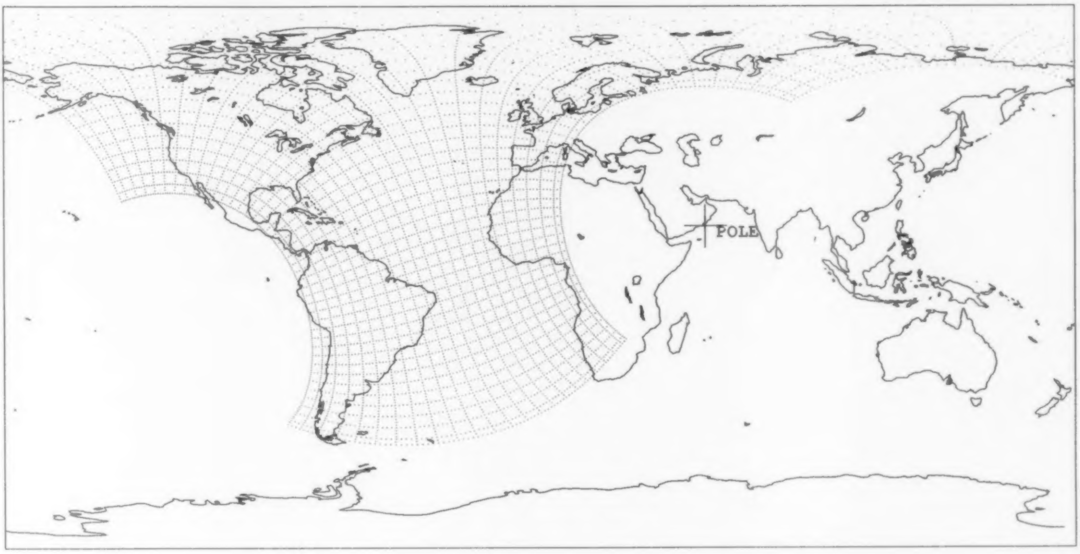

Figure 6. Area which FOAM is expected to cover. Dotted lines represent the mesh to be used by the model, every fourth line of a 1° mesh is shown.

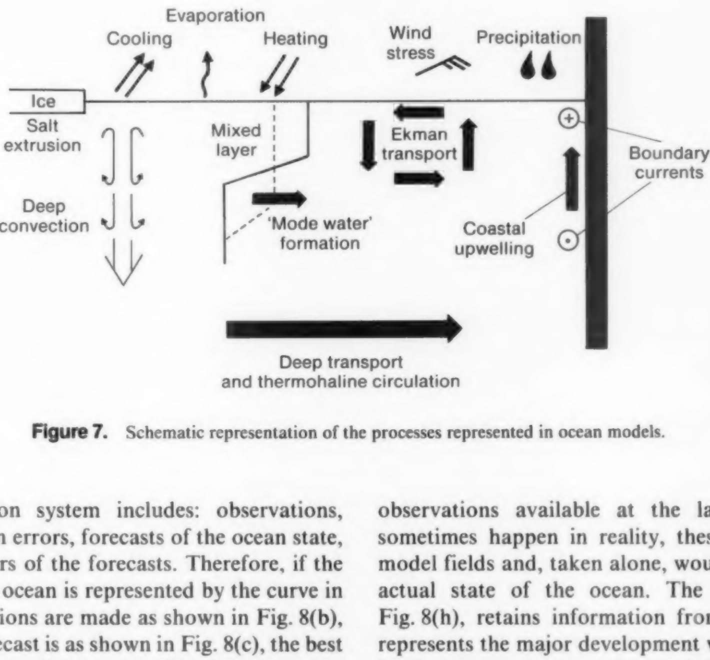

Figure 7. Schematic representation of the processes represented in ocean models.

to the assimilation system includes: observations, typical observation errors, forecasts of the ocean state, and expected errors of the forecasts. Therefore, if the actual state of the ocean is represented by the curve in Fig. 8(a), observations are made as shown in Fig. 8(b), and the model forecast is as shown in Fig. 8(c), the best estimate of the state of the ocean (Fig. 8(d)) does not fit the observations exactly, nor is the forecast field represented precisely. In this case the analysed field is close to the actual state. As time passes the ocean evolves and, because an ocean model forms part of the assimilation system, so does the model estimate of the ocean state. This is illustrated in Figs 8(e) and 8(g). Qualitatively the model and actual fields resemble each other, although errors in the model and the earlier analysis prevent an exact match. Fig. 8(f) shows the observations available at the later time. As will sometimes happen in reality, these add little to the model fields and, taken alone, would misrepresent the actual state of the ocean. The resulting analysis, Fig. 8(h), retains information from the forecast and represents the major development which has occurred. In data-sparse regions the model has the ability to interpolate dynamically in space and time between observations, capturing developments which are not observed directly.

In the FOAM system the assimilation sequence will be performed once each day using a technique similar to that described by Lorenc *et al.* (1991) for an atmosphere model. The assimilation process will consist of an integration of the forecast model with additional calculations performed between the usual forecast steps.

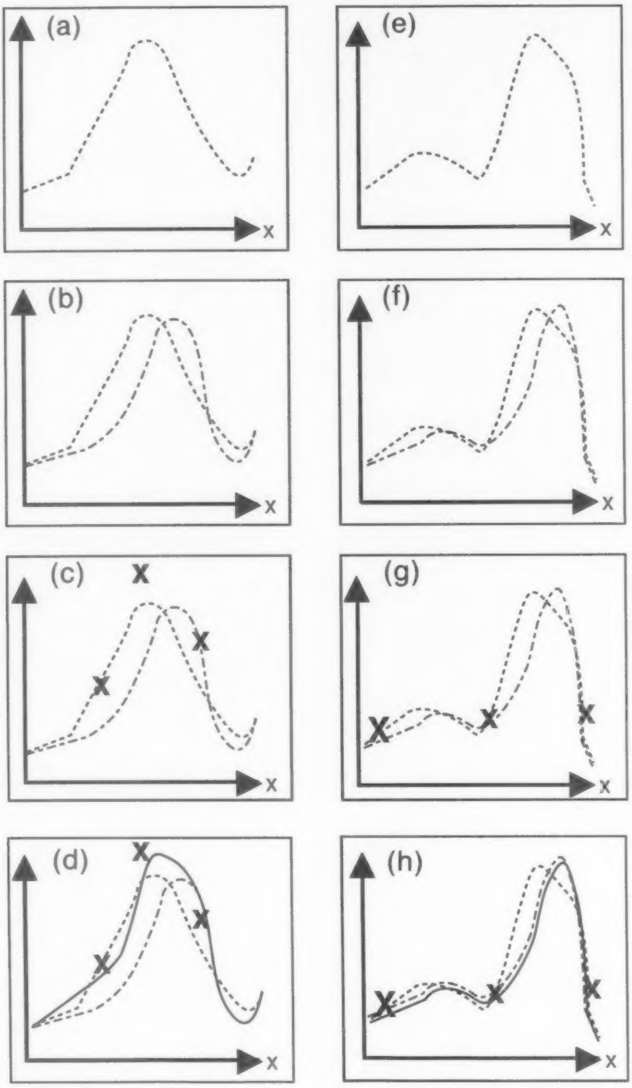

Figure 8. Schematic representation of data assimilation. At the initial time the real state of the ocean is at (a) and is shown dotted in the lower panels. The corresponding forecast is dash-dot (b). Observations are available (marked X) in panel (c). The resulting analysis is a compromise between the observations and forecast (d). At a later time the ocean evolves to the state in panel (e). The forecast (f) carries information not present in the observations (g), and results in a detailed analysis which qualitatively reflects the actual state (h).

These extra calculations will consist of determining the difference between observations and the model values corresponding to each point with observations, and corrections to the surrounding model grid-points to reduce the differences. This 'continuous insertion' of observations results in a smooth adjustment of the model fields towards the observed values. At each time-step the adjustment towards the observations is small, and the model physics have an opportunity to adjust the structure of the model fields to represent the observed values in a manner which the forecast model will be able to use. Without the repeated insertion of observations, an additional stage in the forecast cycle would be required (called 'initialization') in which the fields produced by the analysis would have to be modified to ensure that they were consistent with the needs of the ocean model. Continuous insertion removes the need for an initialization step, and attempts to ensure that the observed values are retained on the scales of motion which the model can represent.

FOAM will use many sources of observations. The order of development of the assimilation scheme reflects their usefulness and the complexity of their use. First to be included will be the BATHY and TESAC reports which are the only direct source of information on the vertical structure of the ocean. Next will be the

ship measurements of sea surface temperature (SST). Satellite measurements of SST will be so numerous that additional techniques will need to be developed to handle them efficiently. After satellite SST data have been included, the more challenging altimeter data will be included. These data must be interpreted and the vertical structure of the ocean deduced from the surface information if the potential of these data is to be exploited. Once these major sources of data have been included other types will be used, such as current data.

Even with global satellite coverage of the ocean surface there will be regions of the ocean which are poorly observed. Most obvious of these is the deep ocean. To prevent systematic errors of the model causing unrealistic fields to develop in data-sparse regions, the FOAM will include a mechanism for adjusting the model fields towards climatology.

6. The role of the oceanographer

Numerical models of the atmosphere and ocean will form the basis of FOAM. Observations will be used to ensure that the model products are an adequate representation of the real world. Results will therefore only be as good as the observations available to the models.

Observations are subject to a number of errors. Some are a result of manual coding of the data, such as transposed digits in a temperature or position. Although such simple errors are easy for a human to identify and correct, it is difficult to automate this process. Thus an oceanographer examining observations which are regarded as suspect by the automated quality control might be able to confirm or correct the observation so that it may be used by the models.

Some observations will not be directly available to the automated system, such as the patterns which can be used to identify eddies in satellite imagery. As a result a second area in which human intervention will be necessary is in creating 'bogus' observations. These will arise from the experience of the oceanographer in interpreting observations and the model data, and will be used to influence the evolution of the model in the same way as real observations. Bogus data may consist of single point observations (analogous to TESAC reports), or may describe a larger-scale entity, such as an eddy. It is planned to introduce a database of typical eddies, fronts, and other 'features' into the FOAM system to allow forecasters to allow rapid and accurate interaction with the models. Feature models have been used successfully by Robinson *et al.* (1988). Some of the features in the database will be tools to allow the correction of broad-scale errors in the model fields (for example to allow an eddy to be removed from the model if one had been introduced in error in an earlier assimilation).

Manual intervention was essential in the southern hemisphere for NWP models before the widespread availability of global satellite observations of the three-dimensional state of the atmosphere in the early 1980s. It is still required for specific features such as tropical storms which are not represented fully by the NWP models. Ocean data are sparser than those for the atmosphere, and there is no prospect of three-dimensional information from satellites. Acoustic tomography, the only remote sensing technique which has the potential to yield three-dimensional fields on basin scales, is in its infancy (Cornvelle *et al.* 1989). Manual intervention will, therefore, be a central part of the ocean data assimilation process for many years.

7. Planned operational system

An overview of the proposed operational system is shown in Fig. 9. The ocean system mimics that used at present for the weather forecast models.

Data are received and placed in the main database. These are examined by an experienced oceanographer

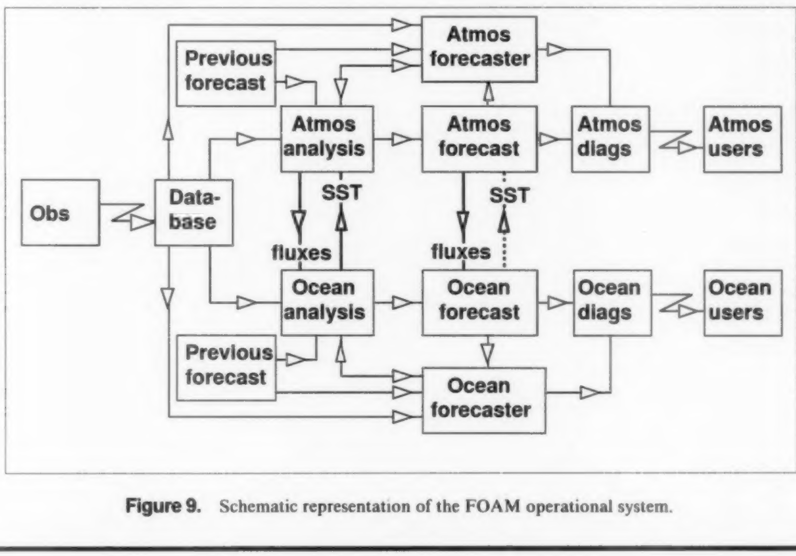

Figure 9. Schematic representation of the FOAM operational system.

who can perform quality control on the observations. Although some quality control will also be performed by the FOAM programs, human experience will be essential if the most value is to be extracted from the few observations available. Examples of errors which a human can rectify more easily than an automatic system include positional errors and transcription errors.

As for the atmosphere forecast models, the ocean forecaster will also be able to influence the model analyses by introducing fictitious 'bogus' observations. As an example of their use, consider a satellite image representing sea surface temperature. A forecaster may be able to identify the positions of several ocean eddies in this. Having identified the eddies, the forecaster can deduce much more information about the ocean structure than the automated system. By introducing additional observations to represent the sub-surface structure, the forecaster will be able to encourage the model to develop realistic representations of the eddies. Instead of introducing a large number of simulated profiles, it is intended that the forecaster will be able to select form a number of conceptual models ('feature models') which would both reduce the workload of the forecaster and improve the consistency of the bogus data. Similar techniques have recently been introduced into the weather forecast models to assist with the analysis of tropical disturbances.

Interactions between the atmosphere and ocean models will initially be loose. Surface fluxes will be calculated during the weather forecast and passed to the ocean model to provide its upper boundary condition. Until the FOAM system had demonstrated its accuracy there would be no feedback from the ocean model to the atmosphere. Once the ocean model had proved its reliability, it would be possible to use the ocean model analyses of sea surface temperature and sea ice as the surface conditions for the next integration of the atmosphere model. FOAM will be based on the Unified Model, and thus will have the mechanisms for coupling the ocean and atmosphere models built in allowing the benefits of coupling the forecasts to be assessed.

8. Summary

Ocean data are sparse and largely describe the surface layer. Information on the three-dimensional structure of the ocean is required on smaller length scales than the observations for any one time can describe. Numerical which the data can interpolate between the observations in both space and time. In performing the interpolation, models can develop features using the physical principles which govern ocean flow. Observations keep the model simulations close to reality, and the models interpolate between the observations.

Computer requirements of high resolution ocean models are so large that until the 1990s it was not feasible to introduce operational forecast models of the ocean. Computer speed will continue to be a limiting factor for model development. Simultaneously with increases in computer power, data from satellites and other sources are expected to increase. The two main restrictions on developing a viable operational ocean forecast system will thus ease simultaneously, making the development of FOAM feasible.

Increased use may be made of observations by using human experience to monitor quality-control decisions made by the automated system. This concentrates the effort where it is most needed, and allows transcription and other common errors to be corrected, enabling the models to use more data.

Some aspects of the observations will not be amenable to automated interpretation. An example is the identification of eddies in the SST fields derived from satellites. Having identified an eddy it may be possible to infer the sub-surface structure from its surface manifestation. Identification of such features is difficult to automate. A man–machine mix is required to produce the best products from FOAM.

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Numerical forecast of the onset of the 1990 seasonal long rains in Kenya

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Summary

Some model fields from the Global Model of the United Kingdom Meteorological Office (UKMO), and 24-hour rainfall data from various stations in Kenya were examined. This was in an attempt to verify whether the model products could have provided useful medium-range guidance in forecasting the onset of the 1990 seasonal long rains in Kenya. The results showed that the model did have some skill, and was capable of predicting the onset of the rains at least two to three days in advance.

1. Introduction

Kenya experiences a bimodal rainfall regime (Johnson 1962, Tomsett 1969, Potts 1971), with the first wet season occurring in the months March to May and the second in the period late October to early December (Kiangi and Anyamba 1987). These rains are commonly referred to as the 'long' and 'short' rains respectively (Mhita and Nassib 1987). The ability to provide accurate short- or medium-range forecasts of the onset of these seasonal rains would not only be important to the agricultural sector, but even more so to the tourism industry, commercial film industries and the general public at large. Studies in the past have shown that it is very difficult to predict the date of the onset of these rains (Thompson 1957, Alusa and Mushi 1974); equally difficult is the definition of an event to mark their beginning (Stern *et al.* 1982).

The case-study given here attempts to verify whether numerical weather prediction (NWP) products originating from the United Kingdom Meteorological Office (UKMO) could have provided useful medium-range guidance in forecasting the onset of the 1990 long rains in Kenya. The region under study, i.e. Kenya, is roughly enclosed by latitudes 4° N and 4° S and longitudes 34° E and 42° E.

It has been assumed that the onset of the 1990 long rains in Kenya occurred on the first day the country experienced widespread rains at the end of the dry season. These rains then continued interspersed with short, dry spells. It has also been assumed that the 'grass' rains that occasionally precede the long rains as noted by Alusa and Mushi (1974) were part of the proper Long Rains. An inspection of the 24-hour rainfall data from various rainfall stations in Kenya (Table I), identified 20 February 1990 as the date of the onset. No attempt has been made in this paper to explain this early onset, and, although generally occurring in early March, there have been other years in the past which had early onsets.

2. Data

The 24-hour rainfall data for various rainfall stations in Kenya were supplied by the Kenya Meteorological Department (KMD). The model products were retrieved from the archive of fields from the operational global forecast model of the UKMO in Bracknell. The version of the model then in use had a grid-point formulation based on the hydrostatic primitive equations with a horizontal grid of 1.875° longitude by 1.5° latitude and 15 levels in the vertical (Bell and Dickinson 1987).

The fields examined were mean-sea-level pressure (MSLP), accumulation of rainfall during the 6 hours preceding the forecast time, and winds at the standard levels 850 mb and 250 mb. Model analyses and forecast periods of 24, 48 and 72 hours were looked at. Observational data of 24-hour rainfall totals provided by the KMD are given in Table I. Due to the difference in the accumulation period for the forecast and observed rainfall and also the fact that data for the former were evenly distributed whilst those for the latter were not, comparisons were made only on the basis of their relative values.

3. Analysis of charts and discussion

3.1 Forecast from data time 12 UTC on 15 February 1990

An increase in the west to east gradient of surface pressure over central Africa is observed during the forecast and is illustrated in Fig. 1; Fig. 1(a) contains the analysis of MSLP and Fig. 1(b) the 72-hour forecast. Consideration of the 1012 mb isobar over the Gulf of Guinea and the 1008 mb isobar in the east shows a general increase in the gradient just to the west of Kenya. A development of this nature tends to induce a more westerly flow of winds in the lower troposphere of the region (Riehl 1954). Thompson (1957) and Kiangi and Anyamba (1987) observed that, at times, rainfall in

Table I. 24-hour rainfall totals (mm) from Kenyan meteorological stations for the 15-day period 12–26 February 1990

Station		Date 12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Northern areas																
Lodwar	(03° 07′N, 35° 37′E)	—	—	—	—	0.1	—	—	0.4	Tr	Tr	11.3	Tr	3.5	0.3	5.4
Marsabit	(02° 18′N, 37° 54′E)	Tr	Tr	—	Tr	Tr	—	Tr	—	5.8	16.0	64.2	—	—	2.0	4.9
Moyale	(03° 32′N, 39° 03′E)	—	—	—	7.1	Tr	—	Tr	16.1	23.0	Tr	4.0	Tr	4.3	3.2	3.0
Garissa	(00° 28′S, 39° 38′E)	—	—	—	—	—	—	—	—	1.1	—	—	—	—	Tr	0.3
Wajir	(01° 45′N, 40° 04′E)	—	—	—	—	—	—	—	—	2.8	—	—	—	16.0	—	2.1
Mandera	(03° 56′N, 41° 52′E)	—	—	Tr	—	—	—	—	—	—	—	—	—	—	—	—
Western areas																
Kitale	(01° 01′N, 35° 00′E)	—	—	—	Tr	—	—	22.6	1.2	2.3	34.4	5.2	2.2	3.4	0.6	—
Kakamega	(00° 17′N, 34° 47′E)	0.4	—	Tr	—	—	24.4	6.8	1.4	18.8	55.3	4.7	1.5	26.6	3.7	0.1
Eldoret	(00° 32′N, 35° 17′E)	—	—	—	—	—	—	—	2.2	10.9	23.4	4.0	49.2	35.5	8.5	1.1
Kericho	(00° 22′S, 35° 21′E)	3.3	—	—	5.8	—	19.0	—	13.6	25.0	33.5	1.5	25.4	41.9	8.3	3.2
Kisii	(00° 40′S, 34° 47′E)	9.1	0.8	0.3	0.6	8.8	58.0	2.9	5.6	2.0	29.0	0.6	1.1	16.1	16.1	7.5
Lake Basin																
Kisumu	(00° 06′S, 34° 45′E)	—	—	—	—	—	21.0	—	1.2	0.5	87.3	0.4	9.9	9.2	1.8	Tr
Rift Valley																
Nakuru	(00° 16′S, 36° 06′E)	—	—	—	—	—	—	0.1	1.1	0.5	20.6	18.7	2.1	8.1	15.3	1.8
Narok	(01° 08′S, 35° 50′E)	—	—	—	2.8	Tr	3.5	—	32.1	Tr	23.0	Tr	0.6	2.8	7.7	30.0
Highlands east of Rift Valley																
Nyeri	(00° 30′S, 36° 58′E)	1.0	—	0.8	Tr	1.4	2.8	Tr	1.6	0.4	30.0	3.3	6.0	0.6	0.1	0.2
Dagoretti	(01° 18′S, 36° 45′E)	—	Tr	—	—	—	—	—	11.8	0.8	8.4	—	0.7	—	—	5.9
Wilson	(01° 19′S, 36° 49′E)	—	—	—	—	—	—	—	8.3	0.3	0.5	—	9.4	—	—	10.3
J.K. Airport	(01° 19′S, 36° 55′E)	—	Tr	—	—	—	—	—	29.4	Tr	0.1	—	6.6	—	—	4.6
Embu	(00° 30′S, 37° 27′E)	—	—	—	—	—	—	—	0.3	0.5	—	5.6	Tr	—	—	—
Meru	(00° 05′N, 37° 39′E)	—	—	0.4	22.2	11.4	—	—	—	0.8	14.1	13.9	Tr	Tr	37.1	4.6
South-eastern districts																
Makindu	(02° 17′S, 37° 50′E)	—	—	—	—	—	—	—	5.6	Tr	0.7	11.8	13.7	—	—	1.4
Voi	(03° 24′S, 38° 34′E)	0.6	—	—	—	—	—	—	1.3	—	—	—	—	—	3.2	0.8
Coast																
Lamu	(02° 16′S, 40° 50′E)	Tr	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Malindi	(03° 14′S, 40° 06′E)	—	—	—	—	—	—	—	—	Tr	—	—	—	—	—	—
Msabaha	(03° 16′S, 40° 03′E)	—	—	—	—	—	—	—	—	Tr	Tr	—	—	—	—	—

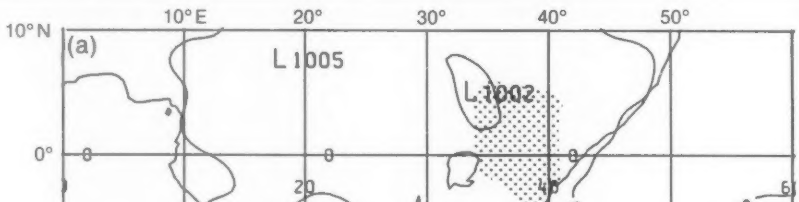

Figure 1. (a) Mean-sea-level pressure (mb) at 12 UTC on 15 February 1990, and (b) 72-hour forecast of 6-hour rainfall accumulation and mean-sea-level pressure valid for 12 UTC on 18 February 1990 (values are in whole millimetres (1–9) or shown as dots (0.1–0.5 mm), A (10 mm), B (11 mm), C (12 mm), etc. Kenya is shown by the shaded area.

Kenya is associated with incursions of unstable westerlies or Congo air, a near stagnant air of high humidity.

Despite this increase in west to east pressure gradient, little or no precipitation is forecast over most of Kenya during the forecast as illustrated by the 6-hourly totals in Fig. 1(b). At 850 mb a largely diffluent flow pattern is dominant over Kenya in both the analysis and forecast, the 72-hour forecast being shown as an example in Fig. 2. A flow pattern of this nature tends to inhibit convective developments (Riehl 1954, Kiangi and Anyamba 1987). At 250 mb there is a generally east or south-easterly flow with little or no diffluence over Kenya. This is apparent throughout the forecast with the 72-hour forecast chart shown in Fig. 3.

3.2 Forecast from data time 12 UTC 17 February 1990

This forecast covers the period of the onset of the rains and a sequence of forecast charts at 24-hour intervals for MSLP and rainfall is given in Fig. 4. An increase in the west to east gradient of pressure is again apparent over central Africa during the forecast, but the 72-hour forecast chart in Fig. 4(d) now shows widespread rain to be predicted over Kenya by this time. This follows 24- and 48-hour forecasts of relatively dry conditions (see Figs 4(b) and 4(c)), and contrasts with the previous forecast described in section 3.1 from a data time two days earlier. The predicted onset of the rains is in good agreement with the date inferred from the observational data in Table I. At 850 mb a line of convergence in the wind field can be identified immediately to the east of Lake Victoria in the analysis (Fig. 5(a)), and moves steadily eastward during the forecast with its position after 72 hours shown in Fig. 5(b). Such a line of convergence would tend to increase the low-level moisture content of the atmosphere, and its forecast movement would imply a surge of westerly or Congo air into Kenya.

During intense surges of westerly air in the lower levels, the effects, which include an increase in precipitation, may be felt as far east as Nairobi (1° 18′S, 36° 45′E). The forecast rainfall charts in Fig. 4 seem to agree with this observation. No marked confluence or diffluence can be observed over Kenya at 250 mb either in the analysis or during the forecast, the 72-hour forecast being given as an example in Fig. 6. Kiangi and Anyamba (1987) have pointed out that upper-level outflow of air from the East African region towards mid-latitude troughs tends to be associated with confluent flow in the low levels.

3.3 Forecast from data time 12 UTC on 21 February 1990

This forecast covers a period after the long rains had started and the sequence of forecast charts for rainfall and MSLP in Fig. 7 shows widespread rain across the country. This sequence also shows the same trend of the two earlier forecasts in increasing the west to east gradient of MSLP.

At 850 mb a convergence line is again in evidence immediately to the east of Lake Victoria in the analysis (Fig. 8(a)), and is predicted to move steadily east during the forecast reaching the extreme east of Kenya after

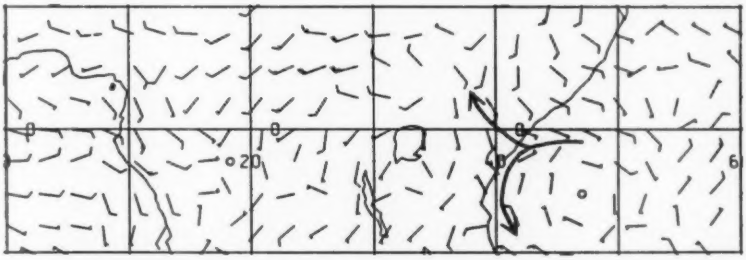

Figure 2. 72-hour forecast of the 850 mb winds valid for 12 UTC on 18 February 1990 with streamlines added over Kenya.

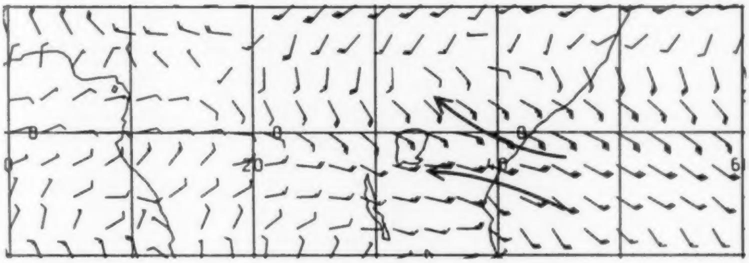

Figure 3. 72-hour forecast of the 250 mb winds valid for 12 UTC on 18 February 1990 with streamlines added over Kenya.

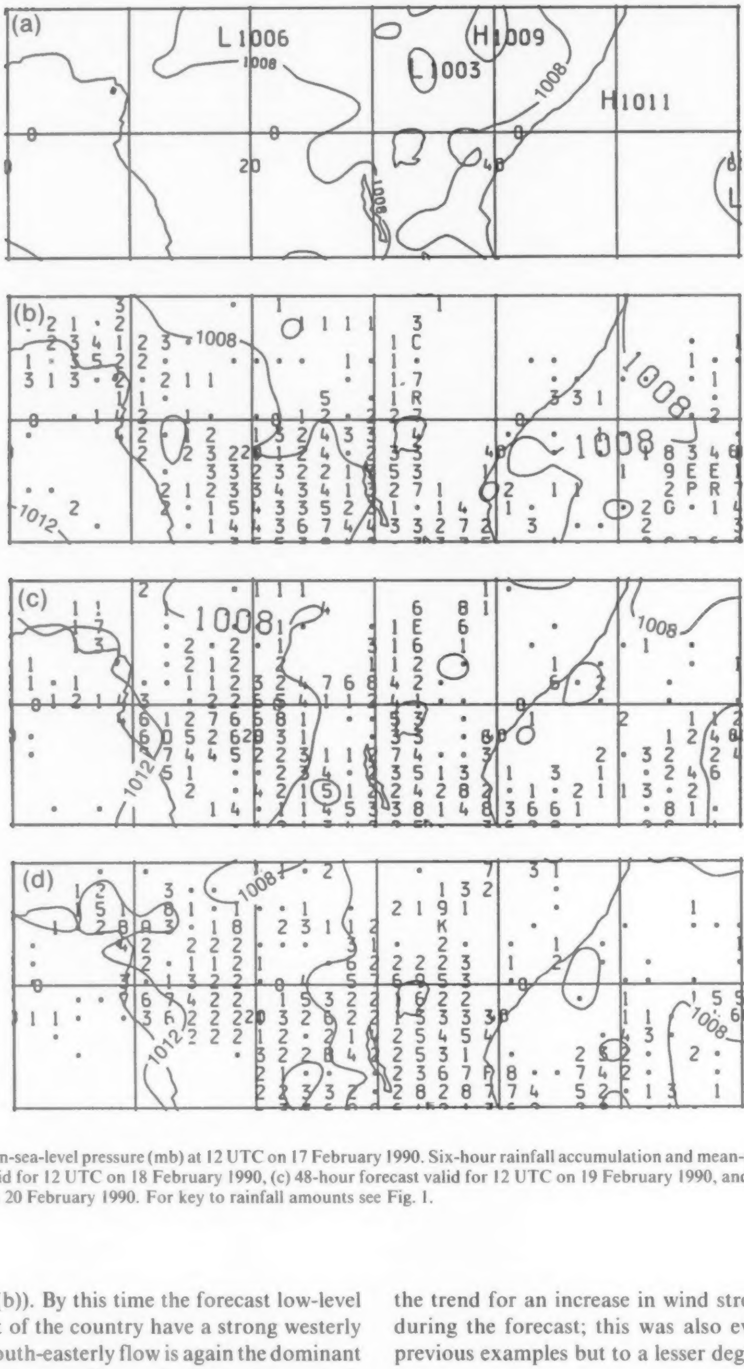

Figure 4. (a) Mean-sea-level pressure (mb) at 12 UTC on 17 February 1990. Six-hour rainfall accumulation and mean-sea-level pressure, (b) 24-hour forecast valid for 12 UTC on 18 February 1990, (c) 48-hour forecast valid for 12 UTC on 19 February 1990, and (d) 72-hour forecast valid for 12 UTC on 20 February 1990. For key to rainfall amounts see Fig. 1.

72 hours (Fig. 8(b)). By this time the forecast low-level winds over most of the country have a strong westerly component. A south-easterly flow is again the dominant feature at 250 mb over Kenya in both the analysis (Fig. 9(a)) and the forecast. The predicted field after 72 hours is shown in Fig. 9(b). A structure of this nature with no marked diffluence in the upper troposphere would not normally be expected to contribute much by way of enhancement or suppression of convective developments over the affected area. Of some interest is the trend for an increase in wind strength over Kenya during the forecast; this was also evident in the two previous examples but to a lesser degree.

4. Summary and conclusions

The principal results from the forecast runs described in section 3 may be summarized as follows:

(a) The onset and spread of rain over Kenya, as indicated by the forecast rainfall charts, are in broad

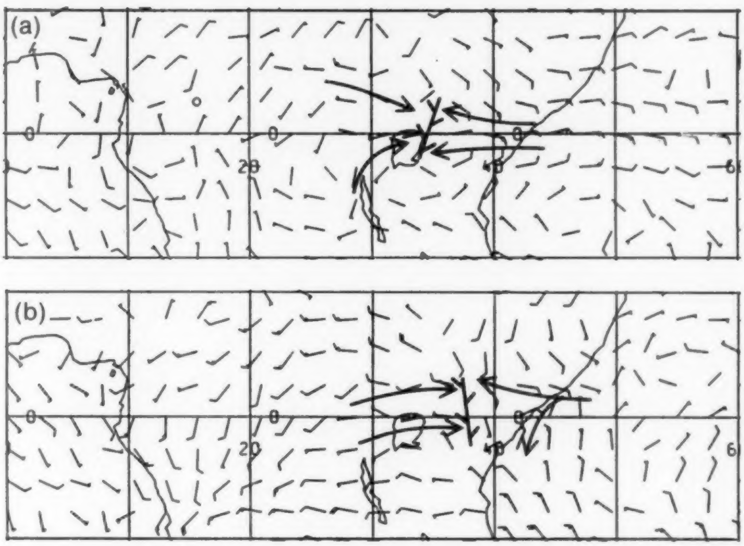

Figure 5. Winds at 850 mb, (a) analysis valid for 12 UTC on 17 February 1990, and (b) 72-hour forecast valid for 12 UTC on 20 February 1990, with streamlines added over Kenya.

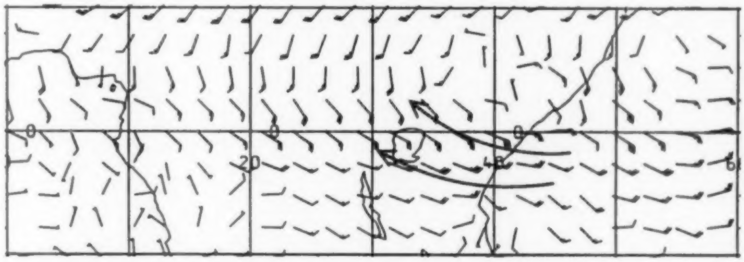

Figure 6. 72-hour forecast of 250 mb winds valid for 12 UTC on 20 February 1990, with streamlines added over Kenya.

agreement with observations.

(b) The forecast charts of MSLP would not have been very helpful in giving the necessary guidance. The otherwise conducive trend to build a west to east pressure gradient during the forecast, occurs in all three examples. It should also be noted that the sequence provided by the analyses in Figs l(a), 4(a) and 7(a) do not show this trend to any marked degree, though this would have been expected.

(c) The 850 mb structure of winds suggests the formation of a line of convergence which shifts eastwards in agreement with the eastward spread of the observed rainfall. This movement of the convergence line, which is first noticed at the start of the widespread rains, is however repeated in the forecast run after the onset. A comparison of Fig. 8(b) with the verifying analysis for this time in Fig. 10 reveals that this pronounced eastward progression is in fact, erroneous.

(d) The 250 mb charts generally show a weakly diffluent pattern, as would be expected at the beginning of the rainy season.

The errors observed on the forecast charts for MSLP and 850 mb winds could possibly be due to lack of adequate additional data in the area under study. In this case, the analyses would closely resemble the background field and the forecasts would often resemble those from the previous run of the model (WMO 1991).

The rains observed over the western and central parts of Kenya before the onset, and not depicted on the forecast charts, could perhaps illustrate deficiencies in both the convective parametrization scheme of the model and the representation of orography. Convective parametrization schemes can have difficulty in handling situations where showers develop in a scattered fashion, and precipitation amounts are generally underforecast in such cases (WMO 1991). Also, poor representation of

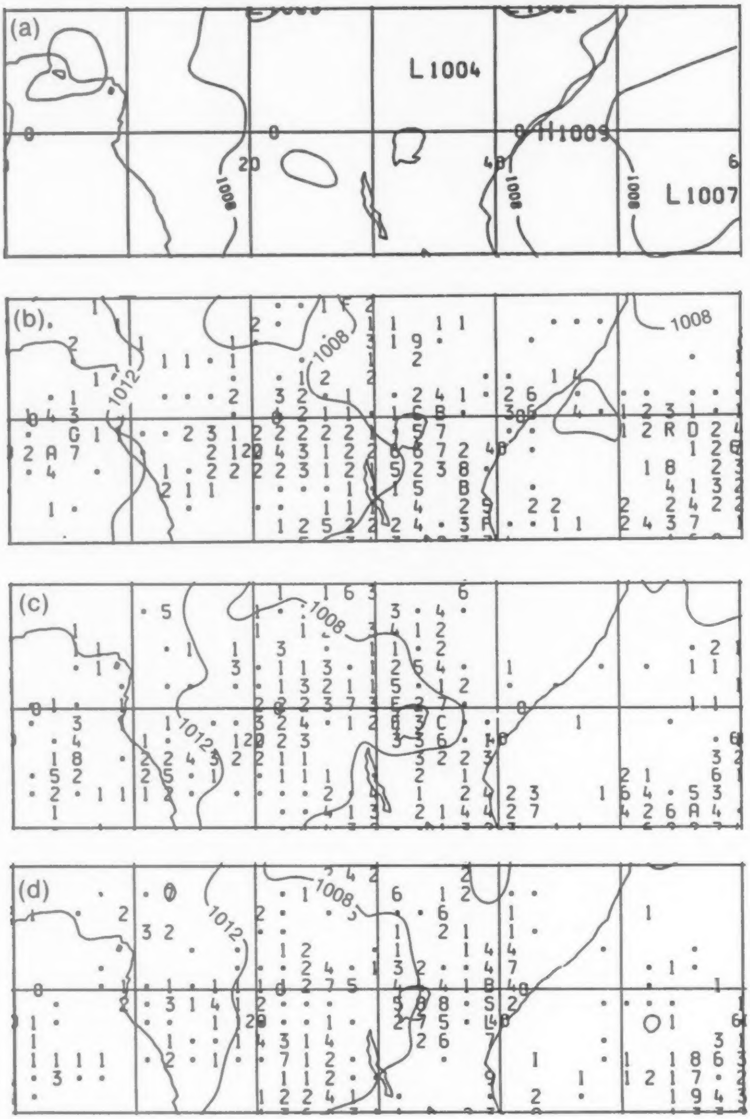

Figure 7. (a) Mean-sea-level pressure (mb) at 12 UTC on 21 February 1990. Six-hour rainfall accumulation and mean-sea-level pressure, (b) 24-hour forecast valid for 12 UTC on 22 February 1990, (c) 48-hour forecast valid for 12 UTC on 23 February 1990, and (d) 72-hour forecast valid for 12 UTC on 24 February 1990. For key to rainfall amounts see Fig. 1.

orography often results in underforecasting precipitation which would otherwise have been enhanced by it (WMO 1991). This study has shown that the model did have some skill and was capable of predicting the onset of the 1990 seasonal long rains in Kenya, at least two to three days earlier. Care has to be taken however, in view of the systematic errors identified in the forecast of MSLP and the movement of the convergence line in the 850 mb wind forecast.

Acknowledgements

This study was made as part of the author's on-the-job training in the interpretation of numerical weather prediction products at the Meteorological Office in Bracknell. Acknowledgements are made to Dr. W.H. Lyne and all the staff in the Central Forecasting Office for their assistance, and thanks are due to the British Government for awarding the VCP fellowship enabling the training programme to be undertaken.

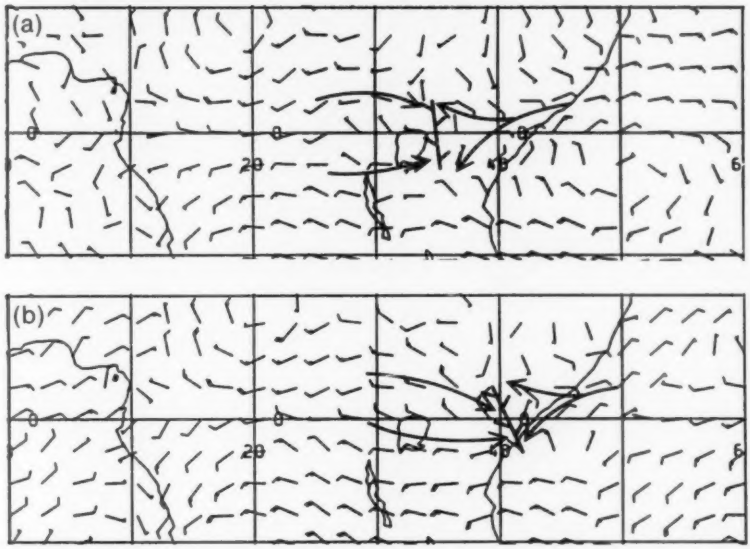

Figure 8. Winds at 850 mb, (a) analysis for 12 UTC on 21 February 1990, and (b) 72-hour forecast valid for 12 UTC on 24 February 1990, with streamlines added over Kenya.

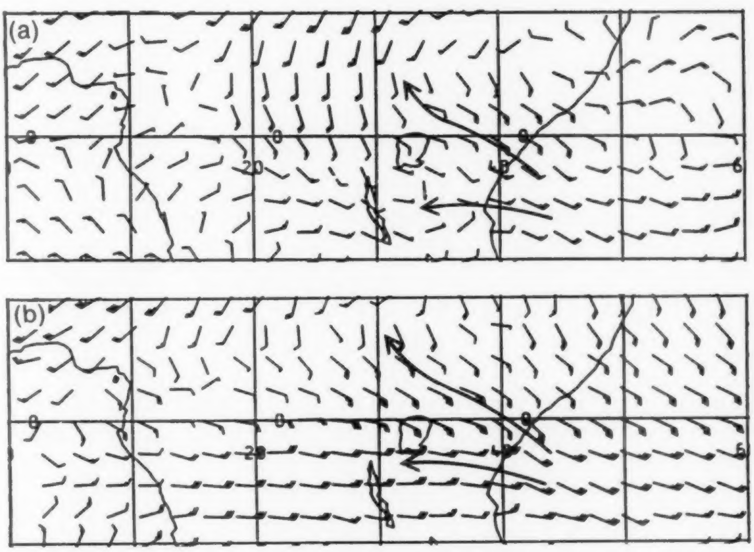

Figure 9. Winds at 250 mb, (a) analysis for 12 UTC on 21 February 1990, and (b) 72-hour forecast valid for 12 UTC on 24 February 1990, with streamlines added over Kenya.

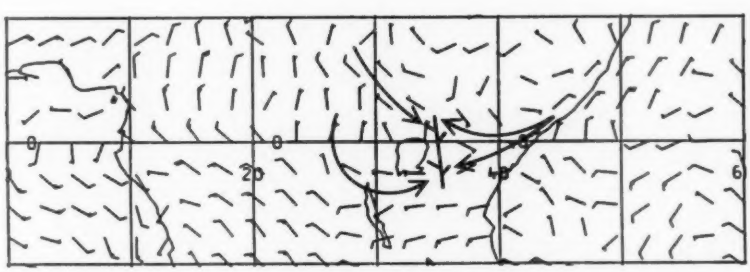

Figure 10. Analysis of 850 mb winds for 12 UTC on 24 February 1990, with streamlines added over Kenya.

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The spring of 1991 in the United Kingdom

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Summary

The spring of 1991 was generally rather warm, wet in the north and west but dry in eastern areas, especially in north-east England, and rather dull in practically all parts of the United Kingdom.

1. The spring as a whole

Mean temperatures over the spring months were above average in most areas, ranging from 1.3 °C above average in North Wales and Dorset to 0.2 °C below average at Girvan, Strathclyde Region. Seasonal rainfall amounts were above average in western parts, but below average in central and eastern areas, ranging from 143% of average at Bargrennan, Dumfries & Galloway to 53% at Cromer, Norfolk. Sunshine amounts over the season were below average nearly everywhere; several places in Scotland having just above average, including a figure of 102% in the Glasgow area. In contrast Harrogate, North Yorkshire had a very dull 58% of average and nearby Bradford, West Yorkshire had 63% of average.

Information about the temperature, rainfall and sunshine during the period from March to May 1991 is given in Fig. 1 and Table I.

2. The individual months

March. March was a warm month especially over central and eastern England, although not generally as warm as March 1990. Mean monthly temperatures were above normal over the whole United Kingdom and ranged from 0.9 °C above normal at St Mary's, Isles of Scilly to 3.1 °C above normal at Cromer, Norfolk. Monthly rainfall totals were above normal nearly everywhere, the exceptions being parts of central and eastern England and the northernmost part of the Western Isles where rainfall was below normal, and ranged from 178% at Tynemouth, Tyne & Wear to as little as 40% at Manston, Kent. Monthly sunshine amounts were below average nearly everywhere apart from a few places in East Anglia and along the south coast, where values were average or just above, ranging from 104% of average at Falmouth, Cornwall to as little as 39% of average at Bradford, West Yorkshire.

The first three weeks were wet, although rainfall amounts were greater in the west than in the east; some parts of the east and south-east were unusually dry for March. North-eastern coastal areas had cold and foggy weather between the 6th and 9th. A tornado hit part of south-west Wales early on the 3rd, causing considerable structural damage and uprooting trees. On the 7th deposits of dust or sand in rainfall were reported at a number of places in the west Midlands, including Malvern, Bromsgrove and Solihull. On the 11th deposits of red dust were reported in rain at Northwood, Greater London and Cavendish, Suffolk. An area of thundery activity extended from Lincolnshire to East Sussex on the 16th. Thunder was reported in Surrey and Berkshire on 21st, the Thames Valley, the Cotswolds and Cornwall on the 22nd and on 23rd there was an isolated thunderstorm in the Thames Valley. During the early hours of the 26th brown rain was reported at Towy Castle, Dyfed and Slimbridge, Gloucestershire.

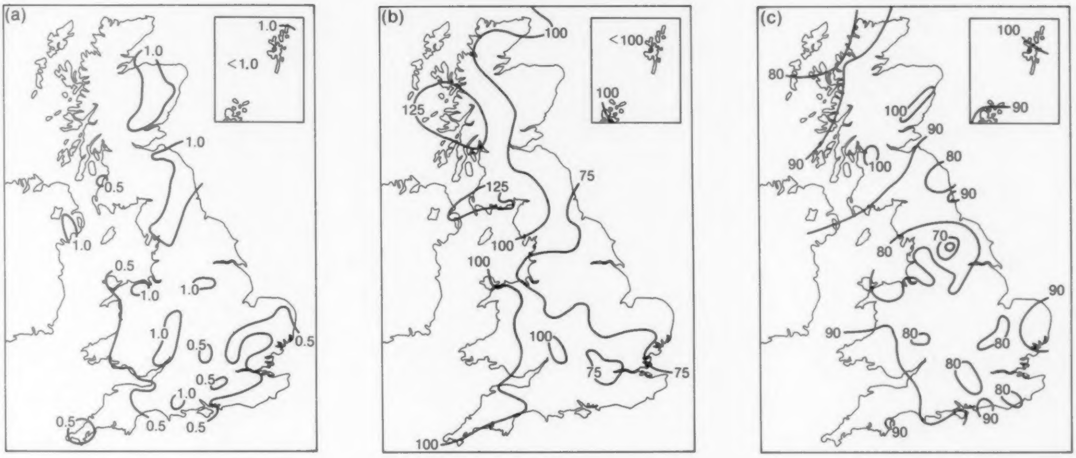

Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for summer, 1991 (March–May) relative to 1951–80 averages.

Table I. District values for the period March–May 1991, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.8	+1	101	89
Eastern Scotland	+0.9	−2	95	91
Eastern and north-east England	+0.8	−2	75	81
East Anglia	+0.5	−2	72	90
Midland counties	+0.8	−3	80	81
South-east and central southern England	+0.4	−2	86	88
Western Scotland	+0.7	−1	120	92
North-west England and North Wales	+0.7	−2	96	80
South-west England and South Wales	+0.6	−1	101	93
Northern Ireland	+0.8	−1	114	91
Scotland	+0.8	−1	109	91
England and Wales	+0.7	−2	88	85

Highest maximum: 25.0 °C in Midland counties in May.
Lowest minimum: −8.0 °C in western Scotland in March.

April. Mean monthly temperatures were generally near to the monthly normal and ranged from 0.6 °C below normal at Sandown, Isle of Wight to 1.2 °C above normal at Kinloss, Grampian Region. Monthly rainfall totals were above normal everywhere except over eastern Scotland and much of northern England, and ranged from more than twice the normal in parts of western Cornwall and western Scotland to less than half the normal in north-east England and around the Moray Firth. Heavy rain gave falls of 72 mm at Inverinan, Highland Region on the 1st and 81 mm at Isle of Rhum, Highland Region on the 10th, the latter having its wettest April day since records began there in 1958. Heavy rain during the 29th and 30th doubled the month's totals in parts of south-east England, with some places having their wettest April day this century on the 29th, the wettest day over England and Wales as a whole since the very wet Bank Holiday, 25 August 1986. Monthly sunshine amounts were generally above average in eastern areas but below average in western areas, ranging from 129% of average at Edinburgh, East Craigs, Lothian Region to a rather dull 73% of average at Stornoway, Western Isles. Stornoway recorded its dullest April since 1975, whereas Lerwick with 122% of its normal April amount had its sunniest April since 1970.

The weather was unsettled at the beginning of the month with rain or showers during the first week, and some sunny intervals. Rain was often prolonged and heavy over western areas. The second half of the month brought a wintry mixture of hail, sleet and snow showers, with longer periods of rain and a few sunny intervals. On the 12th thundery outbreaks occurred over parts of central and south-eastern England. On the 18th

and 19th England and Wales had heavy and prolonged wintry showers, sometimes with thunder, although Wales and south-west England had some good sunny spells. Thunder occurred over Essex on the 21st. There were scattered hail showers on the 22nd and 23rd. Rain in the west on the 25th gave way to thundery showers, while in the north and east it remained dry. Further thundery outbreaks occurred over Wales, the Midlands and Cornwall on the 26th.

May. Mean monthly temperatures were generally about average, ranging from 1.5 °C above normal in parts of Tayside Region to 1.6 °C below normal at Greenwich, Greater London and Wye, Kent. Monthly rainfall totals were well below normal everywhere except for the northernmost part of the Scottish mainland where totals were just above normal. The percentage of normal at Cape Wrath, Highland Region, 124%, contrasts with that in parts of western Scotland and much of south-west England and South Wales where amounts were generally less than 10% of normal. It was the driest May over England and Wales since 1896, and Glasgow had its driest May since 1868. Monthly sunshine amounts were below average nearly everywhere, the exceptions being parts of western Scotland, Devon and Cornwall where sunshine amounts were just above average; amounts ranged from 111% of average at Machrihanish, Strathclyde Region to 60% of average at Manchester. Many eastern and northern areas had one of the dullest Mays this century.

During the first week troughs gave some rain in the north. A brief spell of fine weather during the second week gave some sharp overnight frosts. On the 7th there were some locally heavy thundery showers over parts of southern England and South Wales. After the 10th the predominance of milder westerly winds prevented night frosts in all but a few locations and it was warm during the period, with some rain, mainly in the north-west. During the second half of the month the weather was mainly anticyclonic, although often cloudy, but became sunny and very warm for a time around the 21st, before becoming cold again towards the end of the month.

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Atmospheric transmission, emission and scattering, by T.G. Kyle (Oxford, New York, Seoul, Tokyo, Pergamon Press, 1991. £40.00, $40.00) introduces the physical processes needed to understand the behaviour of radiation in the atmosphere. Various wavelength regions are considered and, while software for solving problems is discussed, an effort has been made to avoid extensive mathematics. ISBN 0 08 040287 9.

Future climatic change and radioactive waste disposal, edited by C.M. Goodess and J.P. Palutikof (Norwich, Climatic Research Unit, University of East Anglia, 1991. Postage and packing only) contains the papers presented at an International Workshop on 1–3 November 1989. The urgency of the radioactive waste problem with its associated long time-scales prompted the organization of the meeting.

Perspectives of nonlinear dynamics, Vols 1 and 2, by E.A. Jackson (Cambridge University Press, 1992. £19.95, $32.95 each) develop the perspectives generated by analytical, topological and computational methods in a variety of contexts. They are aimed at a broad readership across a range of disciplines, with a style intended to stimulate the reader's imagination. ISBNs 0 521 42632 4 and 0 521 42633 2.

A *New Scientist* guide to chaos, edited by N. Hall (London, Penguin Books Ltd, 1992. £9.99) contains a collection of essays explaining the roots of this multidisciplinary phenomenon. Computers' abilities to display and explore the area are demonstrated. ISBN 0 14 014571 0.

Meteorological fluid dynamics: Asymptotic modelling, stability and chaotic atmospheric modelling, by R.K. Zeytounian (Berlin, Heidelberg, Springer-Verlag, 1991. DM 66.00) attempts to develop a rational and coherent theoretical modelling of realistic atmospheric flows. It is aimed at both scientists and students of physics and theoretical meteorology. ISBN 3 540 54446 1.

Solar radiation atlas of Africa, by E. Raschke, R. Stuhlmann, W. Palz and T.C. Steemers (Rotterdam, Brookfield, A.A. Balkema, 1991. £93.75) contains many coloured images for the period 1985-86 derived from the SUNSAT project. The logistics employed are decribed, and a variety of other methods of displaying the results are used. ISBN 90 5410 109 1.

Mountain weather and climate, second edition, by R.G. Barry (London, New York, Routledge, 1992. £60.00 (hardback), £18.99 (paperback)) contains sections dealing with all areas of the subject, with case-studies of selected areas. This edition also includes the results of research during the last decade. ISBN 0 415 07112 7 (hardback), 0 415 07113 5 (paperback).

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Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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Sharp monochrome photographs on glossy paper are preferred; colour prints are acceptable but the use of colour is at the Editor's discretion.

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May 1992

Vol. 121
No. 1438

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ISSN 0026—1149

ISBN 0-11-728983-3